MINERALOGICAL STUDY OF ANGRITE ASUKA-881371: ITS POSSIBLE RELATION TO ANGRITE LEW87051

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Abstract: Antarctic angrites LEW87051 (LEW) and Asuka-881371 (Asuka) have distinctive textural and mineralogical affinities. LEW is porphyritic in texture with zoned olivines (~0.5 mm) widely distributed in a fine-grained groundmass. Several olivines are known to contain Mg, Cr-rich cores which are out of equilibrium with groundmass olivines and are considered to be xenocrysts. Asuka is ophitic in texture with large olivine xenocrysts (some larger than 2 mm across) included in a groundmass. These olivines reach up to Fo_{89}, and are as rich in Cr and poor in Ca as LEW olivine cores. Despite these similarities, the variability of the olivine compositions differs between the two. Olivine cores of LEW are almost homogeneous in composition from one grain to another, while the large olivines in Asuka show significant grain-to-grain variation. Each large olivine xenocryst in Asuka is nearly homogeneous except for the remarkably zoned edge indicating reaction with the surrounding melt. Some small olivine xenocrysts in Asuka (~0.5 mm across) have zoning profiles similar to the two-stage zoning profile observed in LEW olivines. However they are interpreted to have the same origin as the other xenocrysts, with the difference being in the zoning profiles, caused by the effect of off-center cuts through the grains. We propose that the difference between LEW and Asuka olivine xenocrysts is produced by differing degrees of melting. The cores of LEW olivines are more clearly zoned than Asuka xenocrysts possibly due to a higher degree of atomic diffusion in LEW olivine. We previously calculated the cooling rate of LEW olivines and estimated that their burial depth was shallower than 2 m. Our model for the formation of the LEW and Asuka angrites is as follows. Homogeneous olivine crystals with extensive chemical variation from one crystal to another were somehow incorporated into a melt and reheated. In the case of LEW, almost all the olivines except for the extremely Mg-rich ones were totally melted, while in Asuka even the Fo_{70} olivines did not melt. After the melting stage, the groundmass of both LEW and Asuka crystallized. Asuka groundmass minerals have ~2x larger grain sizes than LEW. This difference will reflect differences in burial depth. LEW crystallized near the surface (~2 m) where the degree of melting was larger, whereas Asuka crystallized at a deeper burial depth and yet experienced less heating and melting. More intense melting at a shallower depth suggests an external heat source, possibly impact melting.

1. Introduction

Angrites are a unique class of basaltic achondrite represented by a very ancient crystallization age (4.56 Ga) (*e.g.*, Lugmair and Galer, 1992; Nyquist *et al.*, 1994; Premo and Tatsumoto, 1995) and characteristic mineral assemblages and petrology (*e.g.*, Prinz *et al.*, 1977, 1988, 1990, 1995; Delaney and Sutton, 1988; Goodrich, 1988; McKay *et al.*, 1988b, 1990, 1995; Treiman, 1988; Kallemeyn and Warren, 1989; Mittlefehldt

and LINDSTROM, 1990; YANAI, 1991, 1994; MIKOUCHI *et al.*, 1995b; WARREN and DAVIS, 1995; WARREN *et al.*, 1995). Major constituent minerals of the angrites are pyroxene, olivine, and plagioclase. Reflecting their remarkable richness in refractory elements and poverty in volatile elements, pyroxene is very rich in Ca, Al, and Ti, and is classified as fassaite which projects outside of a pyroxene quadrilateral. Olivine also contains abundant Ca, and kirschsteinite (Ca, Fe-olivine) exists as a primary magmatic mineral and as a phase exsolved during subsolidus cooling. Angrite LEW86010 is the only example which contains coarse exsolution lamella of kirschsteinite in olivine (MIKOUCHI *et al.*, 1995c). Plagioclase is nearly free of Na and K, and its An content exceeds $An_{99.5}$. Despite these interesting characteristics, only four angrites have been found to date. Although Angra dos Reis had been the only known angrite for more than a century, three angrites (LEW86010, LEW87051, and Asuka-881371) were discovered recently in Antarctica (MASON, 1987, 1989; YANAI, 1991, 1993b), and they have offered an opportunity to reevaluate their unusual properties and get a deeper understanding of the angrite parent body (s).

The most recently identified angrite, Asuka-881371, is an 11 g recovered mass (YANAI, 1991, 1993b) and shows an ophitic texture. Large olivine crystals (>2×2 mm in size) are set in a fine-grained groundmass composed mainly of fassaitic clinopyroxene, olivine, anorthite, and kirschsteinite. Olivines and fassaites are extensively zoned and their zoning profiles show distinctive features that indicate their complicated formation process, while plagioclase is almost homogeneous anorthite. As many workers have pointed out (*e.g.,* YANAI, 1993a, 1994; McKAY *et al.*, 1995; MIKOUCHI *et al.*, 1995b; PRINZ *et al.*, 1995; WARREN and DAVIS, 1995), LEW87051 and Asuka-881371 have distinctively similar mineralogy and chemistry. Here, we present results of our analyses for zoned olivines and fassaites, especially xenocrystic olivines observed both in LEW87051 and Asuka-881371, to investigate the possibility that Asuka-881371 experienced a similar crystallization process to LEW87051 on the ground that both angrites contain xenocrystic olivines of very similar chemical compositions.

2. Sample and Analytical Techniques

Petrographic observations were made on two polished thin sections of Asuka-881371 supplied from the Meteorite Working Group (NASA/Johnson Space Center) as a consortium study organized by National Institute of Polar Research (NIPR), Tokyo, Japan. The consortium is led by K. YANAI, P. WARREN, and M. MIYAMOTO. We also examined a thin section of LEW87051 to compare its mineralogy with that of Asuka-881371. The thin section of LEW87051 was supplied from the Meteorite Working Group as a part of the consortium investigation led by G. McKAY.

Backscattered electron images were taken with a JEOL JXA840 scanning electron microscope with an energy dispersive spectrometer (EDS) (Mineralogical Institute, University of Tokyo), and quantitative wavelength dispersive analyses were performed on a JEOL 733 electron probe (Ocean Research Institute, University of Tokyo), a JEOL JCM 733 mk II microprobe (Geological Institute, University of Tokyo) and a Cameca SX-100 automated electron microprobe (NASA/Johnson Space Center). Microprobe analyses were obtained at 15 kV accelerating voltage, and beam current was 12 or 30 nA.

3. Results

3.1. Petrography and mineral compositions

Asuka-881371 angrite (Asuka) is an unbrecciated basaltic rock partially covered with fusion crust (*e.g.*, YANAI, 1991, 1993b, 1994). It is ophitic in texture, consisting of large olivine crystals in a fine-grained groundmass. The groundmass is composed of olivine, fassaite, anorthite, and kirschsteinite with minor opaque minerals (Fig. 1).

3.1.1. Olivine

Olivine is one of the most dominant phases in the PTS. Large olivine grains (Type A olivine) reach up to 2×2 mm in size (Fig. 1). They are euhedral to subhedral. They have large homogeneous cores and distinctive rims (Fig. 2). Some of these olivines are the most Mg-rich olivine in the PTS. The maximum Fo content is Fo_{89}, and it is clearly out of equilibrium with Fe-rich groundmass minerals. The core is rich in Cr (0.3 wt% Cr_2O_3) and poor in Ca (0.2 wt% CaO) compared with the other olivines in the angrite (Cr_2O_3 <0.1 wt%, CaO >0.8 wt%). However, olivines with similar chemical composi-
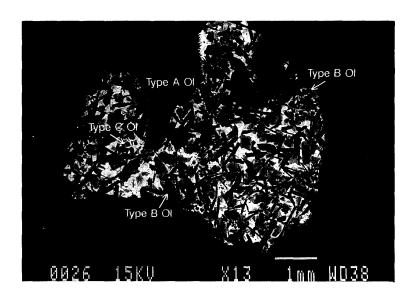

Fig. 1. Backscattered electron (BSE) image of an entire PTS of Asuka-881371. One large olivine crystal (> 2×2 mm) with remarkably zoned rim is included. Gray-colored minerals are zoned olivines and fassaitic pyroxenes. Three typical types of olivine (Type A, Type B, and Type C) are indicated. See text for definitions of these types of olivines. White-colored areas are mainly Ca, Fe-rich olivine and Fe-rich fassaite. Black elongated crystals are anorthitic plagioclase. Scale bar is 1 mm.
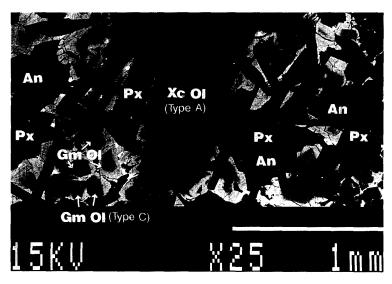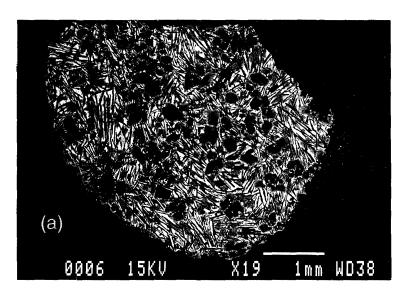

Fig. 2. BSE image of Type A olivine xenocryst (Xc Ol). The rim indicates reaction with the surrounding melt. Large black-colored area in the crystal shows Mg-rich homogeneous composition. An: anorthite, Px: fassaite. Scale bar is 1 mm.

tions have been reported in LEW87051 (LEW) (Fig. 3) (*e.g.,* McKAY *et al.*, 1990, 1991; JUREWICZ and McKAY, 1993; MIKOUCHI *et al.*, 1994a, b, 1995a). These Cr-rich and Ca-poor olivine compositions are observed only in a small portion of the large olivine phenocrysts (Fig. 4). Detailed comparison of the olivines in the Asuka and LEW angrites is made in the next chapter. In Asuka almost all parts of the crystals are homogeneous in chemical composition within each individual crystal, except for the remarkably zoned rims that apparently indicate reaction with the surrounding melt (Fig. 2). However, the core compositions show significant variation from one crystal to another. The most Mg-rich core is Fo_{89}, but less Mg-rich cores of ~Fo_{80} are also found. Some Type A olivines show undulatory extinction, and this does not seem to be due to shock effects.

In addition to the large Type A olivines, there are other Mg-rich olivines whose core compositions range from Fo_{85} to Fo_{70} (Fig. 1) which we call Type B olivines. Type B olivines are smaller than Type A olivines, their cores are rich in Cr and poor in Ca , and unlike Type A olivine, their cores are rather zoned in chemical composition and show two-stage zoning profiles. This is also observed in LEW porphyritic olivines with Cr-rich cores (*e.g.* McKAY *et al.*, 1990, 1991; JUREWICZ and McKAY, 1993; MIKOUCHI *et al.*, 1994a, b, 1995a).

Groundmass olivine is the third type (Type C olivine), and it is also widely zoned from cores to nearly Mg-free rims (Fig. 2). The cores are up to ~Fo_{70} in composition and the most Mg-poor cores of the three types of olivine. Cr and Al both less than 0.1 wt% are much lower than in Type A and B olivines. The rims are very Fe, Ca-rich and show banded textures, possibly due to fine exsolution lamellae of kirschsteinite and Ca-rich fayalite (Fig. 5). Similar exsolution relationships were also observed in LEW groundmass olivines, but the lamellae are much thinner than those of the Asuka Type C olivine and beyond the resolution of microprobe analysis (McKAY *et al.*, 1990; PRINZ *et al.*, 1990). The coarser lamellae are in line with that of the groundmass minerals of Asuka are coarser than those of LEW, possibly due to slower cooling rate of Asuka than LEW. The kirschsteinite and fayalite exsolution relationship indicates an equilibration temperature of *ca.* 1000°C from an experimental olivine thermometry study (DAVIDSON and MUKHOPADHYAY, 1984).

Fig. 3a. BSE image of an entire PTS of LEW87051,2. Porphyritic olivine crystals (~500 μm) are set in a fine-grained groundmass. Olivine is extensively zoned. Several large olivines contain very Mg-rich cores (Fo_{88-92}), which are also rich in Cr, but poor in Ca. Groundmass is mainly composed of anorthite laths, Ca, Fe-rich olivine, and fassaite. Anorthite laths are remarkable in the PTS. The white-colored area is composed of very Fe-rich olivine and fassaite. Scale bar is 1 mm.
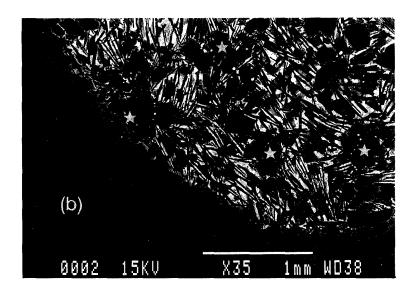
Fig. 3b. Examples of Cr-rich cores of porphyritic olivines in LEW87051. The cores are shown by white-colored asterisks (★) in the figure. Scale bar is 1 mm.
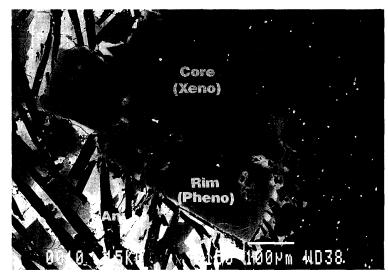

Fig. 4. BSE image of Cr-rich core olivine in LEW87051. This olivine is the most Mg-rich (Fo_{92}) and the largest in the PTS. The crystal can be separated into a xenocrystic inner core (Core Xeno) and a phenocrystic outer rim (Rim Pheno). Scale bar is 100 μm.

3.1.2. Pyroxene

Pyroxene is fassaite. Fassaites are euhedral to subhedral (Fig. 5) and exhibit extensive zoning from pale-colored cores to reddish brown rims. Their sizes are at most about 800 μm across. Al_2O_3 ranges from 5–10 wt%, TiO_2 1–6 wt%, and Cr_2O_3 0.0–0.8 wt%. CaO is almost constant as in fassaites in other Antarctic angrites, but P_2O_5 increases a little towards the rim (0.3–0.5 wt%). Cr and V are positively correlated.

3.1.3. Plagioclase

Plagioclase is homogeneous in chemical composition and is nearly end member anorthite ($An_{>99.5}$). It shows lath texture, and the size is 300 μm in width and 1000 μm in length (Fig. 1). In some areas of the PTS, radiating plagioclase can be observed. The lath texture and radiating plagioclase indicate rapid cooling. FeO (0.4 wt%) and MgO (0.2 wt%) in anorthite are not as high as in LEW anorthite.

3.1.4. Other phases

Minor phases are mainly opaque minerals. They include hercynite, titanian magnetite, whitlockite, and troilite. Prinz et al. (1995) and Warren and Davis (1995) re-

Fig. 5. BSE image of an Asuka-881371 PTS. A very Fe-rich area (gray-colored) surrounding euhedral Type C olivine can be observed and it shows complicated banded texture due to fine-scaled exsolution. The black-colored euhedral crystal in the center of the figure is fassaite. An: anorthite, Px: fassaitic pyroxene, Ol: Type C olivine, Fa: fayalite, and Kst: kirschsteinite. Scale bar is 100 μm.
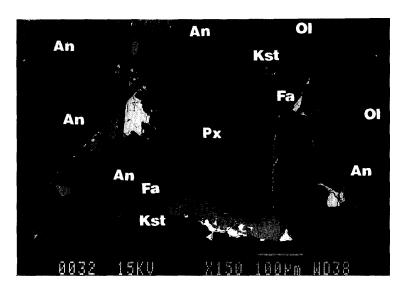
Table 1.   Chemical compositions of each phase of Asuka-881371 (wt%).

	Olivine (Xenocryst)		Olivine (Groundmass)		Fassaite		Plagioclase	Ulvöspinel	Spinel
	Core	Rim	Core	Rim	Core	Rim			
SiO₂	39.63	34.22	37.55	30.58	46.54	41.42	43.84	0.10	0.25
TiO₂	0.05	0.04	0.04	0.10	1.78	3.90	0.03	27.33	1.48
Al₂O₃	0.06	0.06	0.04	0.04	7.82	6.63	35.36	2.42	37.75
FeO	13.54	43.54	28.57	53.38	12.14	26.07	0.37	68.43	31.42
MnO	0.16	0.50	0.34	0.77	0.17	0.16	0.01	0.22	0.26
MgO	45.42	19.63	32.82	0.35	8.19	0.05	0.19	0.02	6.98
CaO	0.28	1.89	0.85	13.49	23.08	21.46	20.20	0.09	0.13
Na₂O	0.01			0.01		0.04	0.04	0.01	0.01
K₂O	0.01			0.01	0.00	0.02	0.01	0.01	
Cr₂O₃	0.34	0.08	0.07		0.38	0.00	0.01	0.01	20.93
V₂O₃	0.04	0.01	0.01		0.11		0.01	0.08	0.60
NiO		0.03	0.02			0.03	0.00	0.03	0.05
P₂O₅			0.04	0.03		0.25	0.01	0.08	
Total	99.52	100.00	100.36	98.75	100.21	100.09	100.06	98.78	99.85
Fe	14.3	53.8	32.4	74.9	21.6	48.6			
Mg	85.3	43.2	66.4	0.9	25.9	0.2			
Ca	0.4	3.0	1.2	24.2	52.5	51.2			

ported an unusual silicophosphate phase. Chemical compositions of some of these minerals are listed in Table 1.

3.1.5. FeO/MnO ratio

The FeO/MnO wt% ratios of the silicate minerals in Asuka are *ca.* 80–90, which are close to those of the silicate minerals in LEW86010 and LEW87051 (Fig. 6). This suggests that Asuka was formed in a rather more oxidizing environment than that of the eucrites whose FeO/MnO wt% ratio is less than 50 (*e.g.*, MITTLEFEHLDT and LINDSTROM, 1990). The acccordance of FeO/MnO ratios between Asuka and LEW is in line with the
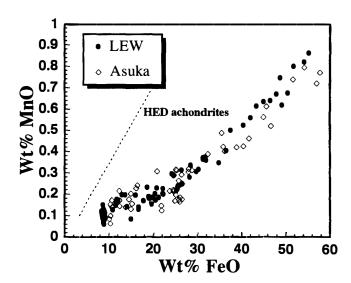
Fig. 6.   Wt% FeO/MnO ratios of silicate phases in Asuka-881371 and LEW87051.

texural and mineralogical similarities between the two.

3.2.   Chemical zoning of olivine and pyroxene

3.2.1.   Olivine

As stated before, it is notable that extremely large olivine (Type A olivine) is included in the PTS (Fig. 1), and Fig. 7 shows its chemical zoning profile. The Type A olivine is almost homogeneous, except for the rim. The Fo content is Fo_{89} in the core, and decreases sharply to $\sim Fo_{70}$ around the boundary of the core and the rim. Finally it reaches very Fe-rich values at the edge of the rim. Cr_2O_3 and Al_2O_3 in the homogeneous core are 0.2–0.7 wt% and 0.1–0.2 wt%, respectively and Cr and Al drop down to ~0.05 wt% at the rim. CaO is around 0.3 wt% in the core. It suddenly becomes Ca-rich at the edge and some outer parts of the rim are kirschsteinite.

The Fo content of Type B olivines is $Fo_{70\text{-}85}$. Cr_2O_3 and Al_2O_3 range from 0.1–0.7 wt% to 0.05–0.25 wt% in the core. CaO also shows variation from <0.05 wt% to 0.7 wt% and CaO and Cr_2O_3 are negatively correlated. Figure 8 shows the zoning profile of Type B olivine. These olivines show an unusual zoning profile, with two stages, as seen in some LEW olivines (e.g., McKay et al., 1991; Mikouchi et al., 1994a, b, 1995a) (Fig. 9). However, the Type B olivines of Asuka have larger homogeneous cores than the two-stage zoned olivines of LEW. Previously, we proposed a relict core model for LEW porphyritic olivines using experimental data measuring Cr and Mn partition coefficients for olivine at various oxygen fugacities (Mikouchi et al., 1994a, b). Our experiments showed that there is no change of Cr and Mn distributions for olivine at $\log fO_2$ from I.W.-2 to I.W.+4 (Mikouchi et al., 1994a; Bajt et al., 1994). In LEW olivine cores, Mn increases as Cr decreases (Fig. 9). In order to explain this different zoning pattern, distribution coefficient of Mn should be below 1, while that of Cr should be above 1. However, the experiment gave opposite results. We concluded that the zoning patterns were produced by atomic diffusion and the core is relict. We also pointed out that the rims of these two-stage zoned olivines show chemical compositions and zoning patterns that are similar to normal single-stage porphyritic olivines, and concluded that the rims
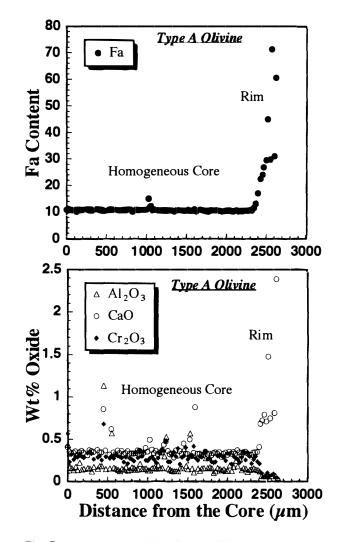
Fig. 7. Fa content, Al_2O_3, CaO, and Cr_2O_3 zoning profiles of Type A olivine in Asuka-881371.

of the two-stage olivines and the cores of the single-stage olivines co-crystallized (Table 2) (MIKOUCHI *et al*, 1995a). The same situation can be observed in Asuka olivines. The rims of some two-stage zoned olivines in Asuka have similar compositions to the cores of groundmass olivines (Fo_{70}, CaO 0.7–0.8 wt%, Cr_2O_3 0.05 wt%) (Table 3). This evidence strongly suggests that the rims of Type B olivines and Type C olivines simultaneously crystallized in the same melt. The transition areas of compositions observed in Type A olivine also has similar compositions. This supports our interpretation that Type B olivines are the same as Type A olivines except that Type B crystals are smaller in size. We believe that smaller size and distinctive two-stage zoning are derived from the effect of an off center cut. If a Type B olivine were cut through its center, its zoning profile would be like that of Type A olivine. This hypothesis is based upon the observation that no large crystals with lengths greater than 1 mm have zoned cores. Instead, all large crystals show large homogeneous cores. Thus, we consider that the unique two-stage zoning of Type B olivines are produced by differences of cut from Type A olivines.

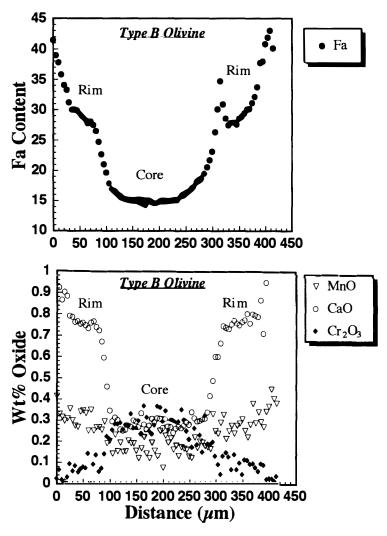Type C olivines are strongly zoned (Fig. 5). They have mantles of Ca-rich olivine

Fig. 8.   Fa content, MnO, CaO, and Cr_2O_3 zoning profiles of Type B
olivine in Asuka-881371.

surrounding their rims and constitute Fe-rich late-crystallized areas between olivine and other phases (Fig. 5). Ti is rich in the Fe-rich rim, although it is nearly free in the inner part. Fa content suddenly reaches nearly Fa_{100} and is almost saturated at the outer part.
3.2.2.   Pyroxene
     Pyroxene is fassaite and its zoning pattern is characteristic. The core has atomic Fe/(Fe+Mg) (fe#) of 0.45, which is more Fe-rich than Type C groundmass olivine. The rim is almost Mg-free, with fe# approaching 1.0. Cr and V are less than 0.1 wt% at the rim, although they are 0.5–0.8 wt% and 0.1 wt%, respectively in the core. Comparing Asuka fassaite with LEW fassaite, both show quite similar zoning profiles as reported by McKAY et al. (1995) and WARREN and DAVIS (1995).

4.   Discussions

     Because all three major phases in Asuka (olivine, fassaite, and anorthite) include euhedral crystals of the others, they crystallized nearly simultaneously. However, the
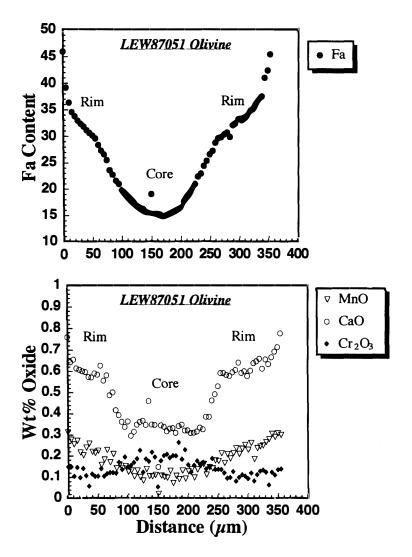
Fig. 9.   Fa content, MnO, CaO, and Cr₂O₃ zoning profiles of two-stage
zoned olivine in LEW87051.

Table 2.   Chemical compositions of LEW87051 olivines.

(wt%)	Cr-rich core olivine				Normal porphyritic olivine	
	Inner part (Core)		Outer part (Rim)			
	Core	Edge	Center	Edge	Core	Edge
Fo	90	80	80	65	80	65
CaO	0.25	0.6	0.6	>1.0	0.6	>1.0
MnO	0.1	0.2	0.2	0.35	0.2	0.35
Cr₂O₃	0.2	0.1	0.1	0.1	0.1	0.1

crystallization sequence is inferred to be olivine, followed by plagioclase, followed by fassaite by combining the experimental crystallization studies for other angrites (McKAY et al., 1988a, 1991).

Type A olivines in Asuka are considered to be xenocrysts from various sources of evidence. The distinct rim features as observed in Fig. 2 indicates contact with the

Table 3.   Chemical compositions of Asuka-881371 olivines.

(wt%)	Type A and B olivines				Type C olivine	
	Relict core		Rim		Core	Edge
	Core	Rim	Center	Edge		
Fo	80–90	70	70	~0	70	~0
CaO	0.1–0.3	0.7	0.7	>1.0	0.7	>1.0
Cr_2O_3	0.3–0.4	0.1	0.1	<0.05	0.1	0.05

surrounding melt. The existence of chemical variations of core compositions from one crystal to another also supports this concept. It will be impossible to produce various compositional olivines from the same melt although the chemical compositions of the olivines are extremely homogeneous within each crystals. Thus, we conclude that Type A olivines appear xenocrysts which have different origins one another.

The most remarkable relationship between Asuka and LEW is that both have similar Cr-rich core olivines. This fact supports our previous model for the LEW formation process (MIKOUCHI *et al.*, 1994a, b, 1995a). We suggested that several Cr-rich cores of LEW olivines are relict grains which survived a melting stage (MIKOUCHI *et al.*, 1994a, b, 1995a). We consider that the cores of Type A and Type B olivines in Asuka are also relict grains as is clear from their xenocrystic nature. The zoning profiles of Type A and B olivines indicate atomic diffusive modification at the boundaries between their cores and the rims. Fe and Cr have longer zoning profiles than Ca, which corresponds to the comparative diffusion rates of these elements in olivines (MORIOKA, 1981; JONES and LOFGREN, 1993). Although Type A olivine has a nearly homogeneous core, the boundary shows Fe enrichment towards the rim. The smaller size Type B olivine has less area of homogeneous core. This is evidence that Type A and B olivines are the same crystals as stated before.

LEW relict olivines have nearly the same chemical compositions between different crystals (Fo_{88-92}), while Asuka relict olivines show significant variations from one grain to another (Fo_{80-89}). However, we suggest that these two olivines may have originated from similar precursor rocks. LEW was heated more intensely during its formation and, as a result, only Mg-rich olivine cores more magnesian than Fo_{88} could remain. Olivines less Mg-rich than Fo_{88} were all melted. In the case of Asuka, because of a lesser effect of heating, olivines of Fo_{80} could survive; their large grain sizes and homogeneous core compositions are preserved. To support this hypothesis, we examined LEW olivine cores again and found that more Mg-rich core olivine have larger area of homogeneous chemical composition. We formerly suggested that some olivine cores of LEW showed zoning profiles from closed-system fractional crystallization (MIKOUCHI *et al.*, 1994b). However, combining the result of Asuka olivines, we now believe it is more likely that LEW cores were originally homogeneous and the zoning profiles were produced by atomic diffusion. The evidence that the Asuka cores are xenocrystic relict further supports the idea that LEW Cr-rich cores are relict.

Another interesting observation is that Type C olivines have similar chemical compositions as that observed at the edges of Type A and B olivines (Table 3). The same situation can be detected in LEW olivines (Table 2). From these results, it is apparent

that groundmass olivines and the rims of xenocryst olivines co-crystallized from the same melt in both meteorites. The groundmass olivines of LEW have Fo_{80} cores, while Asuka Type C olivines are less Mg-rich (Fo_{70-75}). The core composition of fassaite of Asuka and LEW has the same *fe#* of 0.45.

The model we prefer in order to explain the formation of these angrites is as follows. First, olivines crystallized from a primary magma. We suggest that the relict cores of LEW and Asuka have the same origin of the precursor rock. Then, some event which partially melted this parent rock and these olivines remained. In the case of LEW, a higher degree of heating melted more Mg-rich olivine. In the case of Asuka, less intense heating allowed the preservation of the more Fe-rich olivines. After that, the groundmass of a new melt crystallized, reacting with the xenocryst olivines. The difference in the grain sizes of the groundmasses of LEW and Asuka is due to the difference of their cooling rates. This will reflect the difference of burial depth. We estimated the burial depth of the LEW olivine using the chemical zoning of porphyritic olivines (MIKOUCHI *et al.*, 1995a), and according to our results, a 2 m or shallower depth is enough to retain the zoning if we assume that it was covered by rock-like material. This result indicates formation in a shallow lava flow or impact melt sheet. Asuka, with larger grain size, crystallized at a deeper position than LEW in the same or similar lava flow or impact melt sheet containing the relict olivines. However, some difficulty remains in relating the bulk compositions of Asuka and LEW by removal of olivine (McKAY *et al.*, 1995). This might be due to sample heterogeneity by including the olivine xenocrysts. Further investigation of different thin sections is required.

Although it is difficult to determine the heat source of the secondary melting, we speculate that a more intense heating event at shallower depth may reflect an external heating event, possibly impact melting. It is also very difficult to specify the origin of xenocryst olivines. Because they are very Mg-rich, one possibility is that they are residue of partial melt of chondrites, possibly porphyritic olivine chondrule. JUREWICZ *et al.* (1992) showed that angritic melt can be produced by partial melt of carbonaceous chondrites (CV and CM) at high oxygen fugacity. Minor element contents of Asuka and LEW xenocryst olivines are within the range of some chondrite olivines (*e.g.,* JONES, 1992). However, unlike chondrule olivines, Asuka and LEW xenocrysts were originally homogeneous in chemical composition. An oxygen isotope study of these xenocrysts in Asuka also shows no relation to chondrites (WARREN *et al.*, 1995). Another possibility of the origin of xenocrysts is that they are mantle materials which were excavated by impact.

5. Conclusions

(1) Angrite Asuka-881371 is an ophitic basaltic rock. It is mainly composed of zoned olivine, zoned fassaite, and anorthite. An important characteristic of Asuka-881371 is that it contains some large olivine xenocrysts larger than 2 mm across. They are as magnesian as Fo_{89}, and are rich in Cr and poor in Ca. The cores are almost homogeneous in composition within individual crystals, except for zoned edges that indicate reaction with the surrounding melt. On the other hand, different grains have different core compositions.

(2)   Olivines of Asuka-881371 can be classifed into three groups (Type A, B and C). Type A and B are xenocrysts. The smaller size and two-stage zoning of Type B olivine is caused by the effect of an off-center cut through the Type A olivine.

(3)   Angrite LEW87051 has two-stage zoned olivines whose cores are rich in Mg and Cr, and we also consider these cores to be xenocrysts. Thus, both angrites contain olivine xenocrysts. However, they are a little different in their zoning profiles and chemical compositions. This can be explained by differing degrees of melting of the xenocrysts. The cores of LEW olivines are more clearly zoned than Asuka xenocrysts, possibly due to a higher degree of atomic diffusion. In the case of Asuka, large xenocrysts of Fe-rich olivine remain, whereas for LEW, only Mg-rich xenocrysts are present.

(4)   LEW olivine cores and Asuka olivine xenocrysts may have originated from the same source. Compositions of groundmass fassaite and olivine are nearly the same in LEW and Asuka. This indicates formation of the groundmass from similar compositional melts. Asuka groundmass minerals have ~2x larger grain sizes than LEW, possibly reflecting different cooling rates, and thus different burial depths. LEW crystallized near the surface (~2 m). Asuka formed at a deeper burial depth and appears to have experienced less heating and melting. Therefore, we conclude that LEW and Asuka crystallized under similar conditions but experienced different thermal history. We speculate that a more intense heating event at shallower depth may reflect an external heating event, possibly impact melting.

Acknowledgments

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